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LIFE CYCLE MANAGEMENT (LCM)

When consumer behavior dictates life cycle performance beyond the use phase: case study of inkjet cartridge end-of-life management

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Abstract
Purpose Conventional wisdom suggests that product reuse can provide environmental savings. The purpose of this study is to first compare the environmental impacts of retail refilling and remanufactured inkjet cartridge alternatives to production of new inkjet cartridges, and then determine the extent to which consumer behavior can influence life cycle outcomes.
Methods A life cycle inventory was developed for an inkjet cartridge with an integral print head using material composition data collected from cartridge disassembly and material processing, product manufacturing, and transportation inputs estimated from market data and the ecoinvent database in SimaPro 7.3. Although previous comparative life cycle assessment (LCA) studies for printer cartridges typically use "pages printed" or a variation thereof for the functional unit, "cartridge use cycles" is more suitable for examining reused inkjet cartridge alternatives that depend on the inkjet cartridge end-of-life (EOL) route chosen by the consumer. Since multiple reuse cycles achieved from refilling by a retailer was of specific interest, a functional unit defined in the form of "five use cycles" included the mode and manner in which consumers purchased inkjet cartridge use cycles.
Results and discussion Cartridge refills present the lowest environmental impact, offering a 76 % savings in global warming potential (GWP) impact compared to production and purchase of a new inkjet cartridge alternative, followed by the remanufacturing case, which provided a 36 % savings in GWP impact compared to the new inkjet cartridge. However, results varied widely, even switching to favor new cartridge purchase, depending on how consumer transport was modeled, specifically the mode of travel, travel patterns (number of trips), and method of allocating impact to each trip.
Conclusions Refilling an original equipment manufacturer (OEM) cartridge four consecutive times provides the best alternative for reducing environmental impact for those consumers that purchase inkjet cartridges one at a time. On the other hand, consumers that purchase multiple cartridges in a single trip to a retailer reduce environmental impact more by transport minimization than by refilling. Results reinforce the need for more comprehensive inclusion of consumer behavior when modeling life cycle environmental impact of product alternatives.

Keywords Cartridge · Consumer behavior · End-of-life · Inkjet · Life cycle assessment · Refill · Remanufacture

1 Introduction

Public awareness of environmental issues has left consumers wondering what lifestyle changes they can initiate to lessen the environmental impacts associated with consumption. Aside from just consuming less, consumers may reduce their environmental footprint by switching to product alternatives with lower life cycle environmental impacts. Markets have responded with "greener" product offerings; but higher prices and performance concerns discourage widespread adoption. One example is remanufactured products, which have the stigma of being a "used" product, but are considered to be greener, since some remanufactured products require less energy and virgin materials than their new counterparts (Ferrer and Swaminathan 2006; Gutowski et al. 2011).

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Additionally, the lower price of remanufactured products may make them desirable to consumers. A remanufactured product is more likely to be a suitable replacement when the consumer values cost and function over other product attributes, like esthetics. An example of this preference is consumer printer cartridges, which can be refilled for reuse or remanufactured for direct savings to the consumer without significant loss of quality or need to maintain appearance. However, remanufactured and refilled printer cartridges satisfy just 20 % of market demand in the USA (The Recycler 2007). This low percentage can be attributed to market dynamics and a lack of clear guidance for consumers. Since printer original equipment manufacturers (OEMs) use a business model that relies on sales of new inkjet cartridges, OEMs are motivated to protect their revenue stream by discouraging cartridge reuse alternatives provided by independent remanufacturing and refilling firms.

The disparity between new and reused or remanufactured cartridges will likely grow as the market expands. In 2006, 479 million new inkjet cartridges, 85 % of the total cartridge market were shipped to North America (Kasuba 2008). The inkjet printer market is projected to see 5.8 % compound annual growth in the USA through 2014 (InfoTrends 2011a). Increasingly, inkjet printers are preferred over laser printer alternatives, due to performance and cost. Printed page yield for a laser printer cartridge have ranges of the order of 1,000 to 50,000 pages (at 5 % coverage), whereas the range for an inkjet cartridge is typically from 100 to 2,000 pages. The technologies also diverge in price, resulting in a market segmented between high-volume users selecting laser printing technology and home and small business users selecting inkjet technology. Due to cartridge construction differences, laser cartridges must have internal components replaced during a remanufacturing cycle to provide acceptable performance, whereas an inkjet cartridge may be refilled multiple times before degradation in printing is noticeable (Rahmawati and Damanhuri 2009). This inherent durability of inkjet cartridges and the associated profit potential of refilling have prompted inkjet cartridge refilling services to enter the retail landscape, including national retailers Wal-Mart and Walgreens.

While laser and inkjet cartridges provide a similar function in a printing system, their similarities end there, preventing previous laser cartridge LCA research from painting a clear picture of the environmental impacts associated with end-of-life paths and reuse options for inkjet cartridges that were not considered in a 1996 inkjet cartridge LCA (Pollock and Coulon 1996). Results for these studies are summarized in Table 1, with an expanded description of each study in the Electronic Supplementary Material. This body of work has revealed several findings that are relevant for the inkjet cartridge case. In 2002, Berglind and Eriksson demonstrated that environmental savings could be achieved from multiple laser cartridge remanufacturing cycles, while bringing attention to

Table 1 Comparison of LCA parameters and key results for previous cartridge assessments

Study	1996 HP Inkjet	2002 HP C4127X (laser)				2004 HP C4096A (laser)								2008 HP Q2610A (laser)			
Cartridge	OEM	OEM	Rem	OEM	Rem	OEM		Rem-base		Rem-drill and fill		Rem-int'l oper.		OEM		Rem- base	
Paper	No	No	No	10,000 pp	10,000 pp	100 usable pp								100 usable pp			
GWP100	%	kg CO2 eq				kg CO2 eq		kg CO2 eq		kg CO2 eq		kg CO2 eq		kg CO2 eq		kg CO2 eq	
Production	85 %	9.533	5.867	31.033	27.367	0.239	42 %	0.103	20 %	0.059	11 %	0.252	36 %	0.096	12 %	0.095	4 %
Distribution	13 %					0.031	5 %	0.019	4 %	0.002	0 %	0.032	5 %	0.008	1 %	0	0 %
Use	0 %					0.415	73 %	0.438	85 %	0.483	90 %	0.422	60 %	0.72	90 %	0.835	96 %
EOL	2 %					−0.116	−20 %	−0.042	−8 %	−0.009	−2 %	−0.008	−1 %	−0.024	−3 %	0	0 %
Total	100 %	9.533	5.867	31.033	27.367	0.569	100 %	0.518	100 %	0.535	100 %	0.698	100 %	0.8	100 %	0.870	100 %
Recycle	None	Some				Metals		OPC Drum		None				59 %		None	
Waste-to-Energy	Yes	Yes				Balance		86 %						90 %		90 %	
Landfill	Yes	Yes				No		14 %						10 %		10 %	

"OEM" refers to a new cartridge and "Rem" refers to a remanufactured cartridge. The three remanufactured cartridge scenarios considered in the 2004 study were (1) a baseline remanufacturing cycle assumed to be representative of the remanufacturing industry in North America denoted as Rem-Base, (2) a "drill and fill" operation where an empty OEM cartridge is just drilled in order to remove residual and waste toner in the cartridge and then filled with replacement toner, and (3) a remanufactured cartridge produced by an international remanufacturer with improved quality and reliability than the baseline version

the impact of paper and printer electricity, noting that 95 % of the electricity consumed by the printer during the cartridge use cycle occurred while the printer was idle (Berglind and Eriksson 2002). A 2004 study conducted by First Environment proposed a methodology for dealing with quality and page yield difference between a new Hewlett-Packard (HP) laser cartridge and three very different remanufactured versions in the marketplace at that time (First Environment Inc., October 2004). This study was also refreshed in 2008 by Four Elements Consulting, and included a detailed sensitivity analysis (Four Elements Consulting LLC 2008). This literature does not address the scenario of multiple use cycles that may be achieved from refilling one original inkjet cartridge. No study to our knowledge connects this consumer-driven EOL pathway to potential environmental benefits.

The purpose of this study is to provide a consumer-oriented comparison of the environmental trade-offs associated with retail refilling and remanufactured inkjet cartridge alternatives as compared to purchasing new OEM inkjet cartridges. Since a consumer's inkjet cartridge purchase options at any point in time are dependent upon actions taken in previous time periods, our study specifically focuses on: (1) consumer decisions at cartridge end-of-life (EOL), (2) the processing an EOL inkjet cartridge undergoes before returning to the market as a reused (e.g., remanufactured or refilled) alternative, and (3) how consumers purchase inkjet cartridges. Sensitivity and scenario analyses are used to explore assumptions and parameter uncertainties while incorporating observations and data from the inkjet cartridge market to describe the inkjet cartridge alternatives typically found in the US market. Previous LCA results in the print industry suggest consumer behavior during the use phase as the best opportunity for environmental savings from the reduction of paper consumption (Bousquin et al. 2012). Our study fills a gap in existing literature by investigating consumer behavior pertaining to the mode of transportation and manner in which consumers purchase cartridges (i.e., multiple cartridge purchases vs. one-by-one purchasing). Understanding conditions where cartridge reuse can provide environmental savings without sacrificing benefit consumers receive from printed output is explored in this study.

2 Inkjet cartridge LCA

2.1 Methodology and framework

This LCA study was conducted with guidance from the International Organization for Standardization's (ISO's) 14040 and 14044 standards (International Organization for Standardization 2006). The LCA was applied to a monochrome (i.e., black ink) inkjet cartridge produced by Hewlett-Packard, the leader in the consumer inkjet printing market, and was chosen for the following several reasons:

1. The HP 60 inkjet cartridge was designed so that it could utilize plastic recycled from previously used HP inkjet cartridges; an innovative process widely promoted by Hewlett-Packard (Hewlett-Packard 2012).
2. Unlike previous generation inkjet cartridges that specify the amount of ink in the cartridge, the HP 60 cartridge instead identifies an expected page yield of up to 200 one-sided pages at 5 % ink coverage.
3. The HP 60 cartridge is representative of a recent trend in the industry of providing the consumer two replacement inkjet cartridge options, HP 60 and HP 60XL. The HP 60XL is a high-yield version cartridge with up to 600 one-sided pages of expected output. The HP 60 has a lower price than the HP 60XL, but a higher price per page printed as seen in Table 2.

2.2 Goal and scope

The main goal of the study is to evaluate environmental impacts of EOL pathways available to consumers for an inkjet cartridge and determine to what extent the consumer behaviors influence these impacts. Results from this LCA are intended to be used to inform and guide consumers in comparing EOL pathways and inkjet cartridge reuse alternatives. To achieve this goal, specific objectives of the study were to:

1. Determine the life cycle inventory for a representative inkjet cartridge.
2. Compare the life cycle impact of this representative inkjet cartridge with related alternatives available to a US consumer, namely, cartridge refilling performed by a retailer, and purchasing a remanufactured cartridge at a retailer. This comparison will also identify environmental "hotspots" associated with how consumers achieve printed output by the inkjet cartridge options they choose, including the transport mode and manner in which cartridges are purchased. Each scenario includes sensitivity analysis on parameters with high uncertainty to identify conditions under which the environmental preference of inkjet cartridge options may change.
3. Compare the environmental impact of alternative potential waste management options (i.e., recycle, donation, and disposal) for each cartridge option at the end of the use stage.

Table 2 Cartridge prices from Staples®.com on August 3, 2012

Model	Yield	Price	Price per printed page
HP 60	Up to 200 pp	$14.99	$0.075
HP 60XL	Up to 600 pp	$34.99	$0.058

2.3 Functional unit

The function of an inkjet cartridge is to enable a user to print output, and it is only one part of a printing system, which includes a printer, print media, a computer, or other device used to transmit data to be printed. Although there may be differences between the quality and quantity of pages printed across each cartridge alternative, the baseline assumption was that the quality and quantity of pages printed would be identical for each cartridge alternative. Although previous comparative life cycle assessment studies listed in Table 1 for printer cartridges typically use “pages printed” or a variation thereof for the functional unit, basing results on cartridge use cycles allows for more direct focus on impacts specific to the inkjet cartridge EOL route chosen by the consumer, regardless of use. Previous studies, which all assume 100 pages of printed output, also introduce a metric of “usability” for the printed output, and their results show that perceived quality differences in printed output can have a substantial influence on the life cycle impact. To be conservative, our study assumes that each inkjet cartridge alternative provides sufficient quality so that all 100 pages of printed output are usable. This assumption reflects the market, where reputable remanufacturers and retailers offering refill services offer a money back guarantee (Cartridge World 2012; Walgreens 2012). Since multiple reuse cycles achieved from refilling by a retailer was of specific interest, the functional unit was defined as “five use cycles.” This functional unit enables comparison of five new cartridges, one new cartridge reused four subsequent times, or any combination that provides functionality of five cartridge uses.

2.4 Processes and assumptions

Figure 1 shows the processes included for the comparative life cycle assessment of five inkjet cartridge use cycles when a consumer has the choice of purchasing a new or remanufactured cartridge upon their first visit to the retail store. After a use cycle, only a new (or previously refilled) inkjet cartridge may be routed for refilling up to a maximum of four times. Every EOL pathway, except disposing of an empty inkjet cartridge into the municipal waste stream (MSW), requires the consumer to undertake a transportation activity. For consistency, each consumer transport activity is held constant across compared scenarios. After an inkjet cartridge use cycle, the consumer chooses an EOL route for the spent cartridge, independent of the choice for which inkjet cartridge alternative to purchase, except for when the consumer chooses the “Refill” EOL route. Assumptions and specific details for blocks shown in Fig. 1 are as follows:

2.4.1 OEM cartridge

To generate a baseline for comparing cartridge EOL alternatives, a new HP 60 inkjet cartridge was disassembled and then modeled using life cycle inventory data available in the

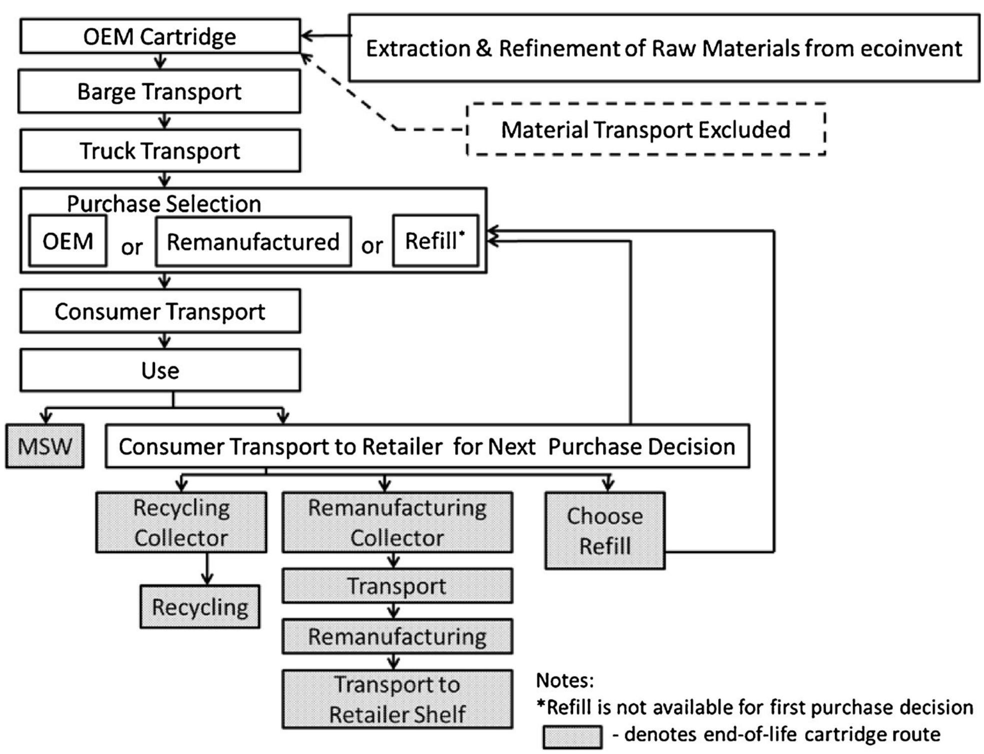

Fig. 1 Processes considered for inkjet cartridge LCA identifying EOL and reuse routes

ecoinvent v2.2 database (Weidema and Hischier 2006) in SimaPro 7.3 (PRe Consultants 2011). Since the exact origin of each component/material could not be verified, European data electricity was assumed and no additional transportation operations were added to account for each component/material to travel from its manufacturing origin to the final cartridge assembly location. The disassembled inkjet cartridge was categorized into the following seven subassemblies/named components and summarized in Table 3:

- **Housing**—the inkjet cartridge housing is composed of 85 % polyethylene terephthalate (PET) and 15 % glass fiber formed into two pieces (ink well and top cover) through injection molding. The ink well is the primary structure used in additional processing steps to mount components and subassemblies in producing a finished inkjet cartridge. The top cover is used near the end of the production process to seal the ink within the cartridge. The entire subassembly weight was used for injection molding processing.
- **Circuitry**—the inkjet circuitry is made of a network of conductors that connect to the print head and interface to circuitry residing in the printer. This circuitry is similar to a ribbon cable that may be found to connect a monitor to the motherboard of a laptop computer, with connections similar to those found in integrated circuits where the

Table 3 Bill of materials and processes for the manufacture of one OEM inkjet cartridge

BOM level	Assembly/material	ecoinvent material/process used	Amount (g)
1	Housing/polyethylene terephthalate (PET)		23.64
1.1		Polyethylene terephthalate, granulate, bottle grade, at plant/RER	20.09
1.2		Glass fiber, at plant/RER	3.55
Process		Injection molding/RER	23.64
2	Inkjet circuitry/flexible printed circuit board		0.1
2.1		Copper, secondary, at refinery/RER	0.015
2.2		Gold, secondary, at precious metal refinery/SE	0.001
2.3		Ethylvinylacetate, foil, at plant/RER	0.03
2.4		Integrated circuit, IC, logic type, at plant/GLO	0.004
2.5		Cable, ribbon cable, 20-pin, with plugs, at plant/GLO	0.05
Process		Production efforts, transistors/GLO	0.1
3	Cartridge label/low density polyethylene (LDPE)		0.05
3.1		Packaging film, LDPE, at plant/RER	0.045
3.2		Adhesive for metals, at plant/DE	0.005
Process		Production of carton board boxes, offset printing	0.05
4	Ink delivery system/foam		1.34
4.1		Polyurethane, rigid foam, at plant/RER	1.34
5	Print head/semiconductor		0.11
5.1		Adapted from integrated circuit, IC, logic type, at plant/GLO (removed epoxies and lead)	0.11
6	Ink/solvent-based ink		15
6.1		Water, deionised, at plant/CH	11.7
6.2		Pentane, at plant/RER	1.05
6.3		N-methyl-2-pyrrolidone, at plant/RER	1.05
6.4		Carbon black, at plant/GLO	1.05
6.5		Butane-1,4-diol, at plant/RER	0.15
7	Inkjet packaging/multiple materials:		35.12
7.1	Low-density polyethylene	Packaging film, LDPE, at plant/RER	0.19
7.2	Paperboard	Corrugated board, recycling fibre, double wall, at plant/RER	1.76
7.3		Corrugated board base paper, wellenstoff, at plant/RER	24.58
7.4	Paper	Paper, woodfree, coated, at integrated mill/RER	5.63
7.5	Pigments	Pigments, paper production, unspecified, at plant/RER	1.8
7.6	Foil	Sealing tape, aluminum/PE, 50 mm wide, at plant/RER	1.16
8	Cartridge assembly	Adapted from average metal working Steel/RER (substituted 0.23 kg PET for steel)	75.36

cable connects to the print head. The circuitry was estimated to contain copper, gold, ethylvinylacetate foil, integrated circuit, and ribbon cable, all materials available in the ecoinvent database. Processing was estimated using production efforts for transistor manufacturing.

- **Label**—a printed label is applied with adhesive to the inkjet cartridge in one of the final production steps. A LDPE film material, adhesive and printing operation that best represented the OEM label from the inkjet cartridge under study, was selected from the ecoinvent database. Printing of the label was estimated using "production of carton board boxes, offset printing" in the ecoinvent database.
- **Polyurethane foam**—a block of polyurethane foam is used inside the inkjet cartridge housing for the ink delivery system; the cartridge was weighed post use, so some portion of dried ink contained in the foam increased its weight.
- **Print head**—the thermal inkjet print head integrated into the inkjet cartridge is a sophisticated device that enables ink to move from the holding tank onto print media. Over time, the print head has evolved to contain the passive thermal inkjet heater circuitry with simple metal oxide semiconductor (MOS) transistor drive circuitry incorporated on the same substrate similar to an integrated circuit (Aden et al. 1994). Due to the proprietary nature of the print head design and manufacture, the choice was made to represent the print head as an integrated circuit from the ecoinvent database as a reasonable proxy.
- **Ink**—the ink found in OEM inkjet cartridges is formulated to work in unison with the printer, paper, and specific cartridge design to provide optimal printing performance. OEM ink formulations are proprietary, highly protected trade secrets. However, a comparable ink formulation was used in this study (Hewlett-Packard Company 2008; Photo Marketing Association International 2004); primarily consisting of deionized water, followed by the addition of various solvents, and carbon black for color.
- **Packaging**—the packaging represented in this study is reflective of Hewlett-Packard packaging which included: (1) a postage-paid return and recycling envelope (which was discontinued in 2008) so that the consumer could send their empty inkjet cartridge to the OEM's designated recycling center, (2) a low density polyethylene (LDPE)/foil wrapper around the cartridge, (3) an instruction sheet, (4) a printed paper board box to display the product, and (5) a representative portion of the corrugated case packaging was allocated to an individual cartridge. Processing steps for packaging was assumed to be represented in the inkjet assembly processing. Since packaging represents a significant portion (47 %) of the total weight of a new packaged inkjet cartridge, manufacturers continue to refine inkjet cartridge packaging.

Manufacturing processing required to produce an inkjet cartridge involve a wide range of activities from plastic injection molding, electronic manufacturing, and highly accurate robotic assembly. This wide variety made it difficult to select a reasonable proxy available in ecoinvent. Inkjet cartridge manufacturing was estimated using a steel processing block in ecoinvent by substituting PET for steel. Since steel production involves processes similar to injection molding and utilizes a similar amount of automation, this choice seemed reasonable.

2.4.2 Barge and truck transport

An inkjet cartridge may be produced at any one of four Hewlett-Packard inkjet cartridge manufacturing locations (Singapore, Malaysia, Puerto Rico, and Ireland). Each location was equally weighted in calculating transport distances for a cartridge to be shipped to Rochester, NY, USA. It was assumed that cartridges produced in Singapore and Malaysia were shipped via ocean freighters to a port in Los Angeles and then transported via large truck to Rochester, and cartridges produced in Puerto Rico and Ireland were shipped via ocean freighters to a port in New York City and then transported via large truck to Rochester as shown in Table 4.

2.4.3 Purchase decision

Since the focus of the study is aimed to inform consumers, the infrastructure and operation of a retailer offering OEM and remanufactured inkjet cartridges for sale was not included in the study. This block represents the consumer's decision process for determining which inkjet cartridge alternative to purchase, and does not consist of any actions that contribute to environmental impact in itself. But the manner in which a consumer purchases cartridges may have a profound effect upon environmental impact. In our study, five cartridge use cycles could be achieved in many ways, such as by a

Table 4 Cartridge transportation estimates

Transportation activity	Mode	Amount (kg-km)
Manufacturer to US Ports	Transport, barge/RER	679
US Ports to Rochester, NY	Transport, lorry >16 t, fleet average/RER	181

consumer purchasing five OEM inkjet cartridges in one trip to a retailer, or purchasing an OEM cartridge in the first trip to a retailer, followed by four subsequent trips to get the empty OEM cartridge refilled. Our base case assumes consumers purchase cartridges one at a time. Purchasing multiple cartridges at one time and varying combinations of cartridges and alternatives are considered in sensitivity analysis.

2.4.4 Consumer transport

The base case assumes that the consumer travels 4 kilometers to a retailer to either purchase a new or remanufactured cartridge, or to have their existing cartridge refilled, an assumption based on a LCA that investigated retail DVD rental locations in Ann Arbor, MI, USA (Sivaraman et al. 2007). The base case assumes the consumer uses an automobile to make a dedicated visit to a retailer to purchase a single cartridge or refill a cartridge, so 100 % of the impact from that trip is allocated to the cartridge life cycle. Certainly, there will be situations when consumers combine purchasing a cartridge or cartridge refill in conjunction with other errands or planned commutes, which would reduce the allocation of transport impact to as low as zero-percent attributable to the cartridge. Impact from low or zero-percent allocation cases would be the same as if the consumer selected low or zero-impact forms of transportation (e.g., public transportation, walking, or bicycling). Sensitivity analysis is used to assess the change in net environmental impact due to variability in (1) the mode of transportation, (2) degree to which consumer transport is allocated to the purchase of a cartridge alternative, and (3) the consumer purchase decision and manner (one cartridge alternative at a time versus five OEM or remanufactured cartridges purchased all at once). These analyses are summarized in Table 5.

2.4.5 Use

Since our study explores EOL routes and reuse options for inkjet cartridges, the base case scenario excludes use phase impacts which have been adequately addressed by previous laser cartridge LCA studies summarized in Table S1 and expanded in the Electronic Supplementary Material. However, in order to compare our findings with these previous printer cartridge LCA studies, we have also considered a scenario that includes use phase impacts. For this scenario, use phase includes 100 pages (8.5”×11” size) of output at 5 % ink coverage using uncoated 20 lb. copy paper and electricity required for printing. The representative printer (Hewlett-Packard Deskjet F-4280) consumes 17 watts when printing, with an estimation of 4 min required to print 100 pages. The US waste scenario in the ecoinvent database was selected as the waste treatment option.

2.4.6 Retail inkjet cartridge refill

Though there are several avenues to refill an inkjet cartridge, such as home refilling and cartridge exchange services, this study is focused on retail refilling since it is a rapidly growing service with widespread availability in the United States (Brewer 2011a, b). Unlike a cartridge exchange service where cartridge ownership is transferred, retail refilling allows for the consumer to retain ownership and track how many times a given cartridge has been refilled. A retail refill was modeled assuming a commercially available inkjet cartridge refilling machine was used to refill a cartridge. Materials and energy required to refill a cartridge were included, but materials and processes required to build and transport the refilling machine to the retailer were excluded.

2.4.7 Remanufactured inkjet cartridge

A remanufactured inkjet cartridge is an inkjet cartridge that has undergone processing by a third party that includes filling the cartridge with ink and packaging comparable to packaging of a new OEM inkjet cartridge. A remanufactured cartridge can vary in environmental impact due to numerous factors, some of which have been considered in previous printer cartridge LCA studies detailed in the Electronic Supplementary Material. Our base assumption assures that the remanufactured cartridge performs on par with an OEM cartridge. However, differences among remanufacturers will ensure variability in environmental impact for any given remanufactured cartridge (that satisfies our performance assumption) on the market at any point in time. Based upon market observations and industry data (InfoTrends 2011b), there are three sources of variability in remanufactured cartridge environmental impact investigated in this study: (1) spent cartridge travel distance, (2) spent cartridge quality, and (3) remanufacturer efficiency. Specifically, two spent cartridge travel distances (500 and 2,300 miles), two input cartridge quality levels (virgin and mixed), and three remanufacturing efficiencies, expressed as the number of cartridges required to produce one remanufactured cartridge (1.09 representing high efficiency, 2.33 representing moderate efficiency, and 3.57 representing low efficiency) are examined. Spent cartridge collection operations are modeled by a collector traveling 300 miles with a small truck, and then the remaining travel distance is modeled using a large truck. A “virgin” cartridge is an OEM cartridge that has undergone one use cycle, where the “mixed” cartridge quality designation consists of a blend of 25 % virgin and 75 % non-virgin cartridges. In the USA, consolidation has resulted in a small number of large volume cartridge remanufacturing facilities. We assume the base remanufactured cartridge in our study is produced by a highly efficient remanufacturer from a virgin cartridge that traveled 2,300 miles to the remanufacturing

Table 5 Base assumptions and sensitivity analysis performed for each scenario

Factors examined	Five OEM inkjet cartridges		Five remanufactured inkjet cartridges		One OEM inkjet cartridge refilled four times	
	Base assumption	Sensitivity analysis	Base assumption	Sensitivity analysis	Base assumption	Sensitivity analysis
Supplier	Hewlett-Packard using 100 % virgin PET	Vary recycled PET content (0, 30, 50, 70, and 100 %)	Highly efficient independent remanufacturer using only virgin inkjet cartridges that were transported 3,700 km	Efficiency (high, low); input quality (virgin, mixed); cartridge travel distance (800 km, 3,700 km)	Retailer offering inkjet cartridge refill service	Failed refill attempts
Purchasing manner	One cartridge at a time, requiring five roundtrips to a retailer located 4 km away	Multiple cartridges purchased at one time	One cartridge at a time, requiring five roundtrips to a retailer located 4 km away	Multiple cartridges purchased at one time	The same cartridge refilled one at a time, requiring five roundtrips to a retailer located 4 km away	Not applicable
Consumer transport mode	Automobile	Walking	Automobile	Walking	Automobile	Walking
Consumer transport allocation	Dedicated trip (100 % allocation)	Vary allocation (0, 10, 50, and 100 %)	Dedicated trip (100 % allocation)	Vary allocation (0, 10, 50, and 100 %)	Dedicated trip (100 % allocation)	Vary allocation (0, 10, 50, and 100 %)

facility. The transport distance by large truck that a remanufactured cartridge travels to a retailer in Rochester, NY, USA is fixed at 1,273 miles.

2.4.8 MSW and recycling

Municipal solid waste (MSW) was modeled using the US Waste scenario in the ecoinvent database. Inkjet cartridge recycling assumed that only the plastic housing (primarily PET) was recovered and used in the production of new OEM inkjet cartridges.

2.5 Impact assessment

Impact assessment was carried out in SimaPro 7.3 LCA software using cumulative energy demand (CED) version 1.07, global warming potential (GWP) over 100 years using IPCC 2007 GWP 100a, and ReCiPe Hierarchist Midpoint World method. CED and GWP were chosen as representative proxies for environmental impact for three reasons: (1) no activity related to inkjet cartridges considered in this study poses human health risks beyond those indicated by CED and GWP100, (2) ReCiPe impact assessment method results were found to trend as CED and GWP100 categories, and (3) GWP allows comparison to findings from previous printer cartridge LCA studies that reported results using GWP impact assessment (although some previous studies use GWP100a based on IPCC assessment reports prior to 2007). Results are shown using either GWP100 or CED when the two assessment methods track similarly, and when these indices differ, results are presented with both assessment methods.

Table 6 shows the ReCiPe (H) Midpoint results by impact category for the five OEM inkjet cartridge scenario when cartridges are purchased one at a time with the consumer making a dedicated trip by automobile to the retailer each time. Since the five OEM cartridge scenarios had the highest values for each impact category, the environmental savings for the base Remanufacturing and Refilling scenarios are shown in Table 6. The largest savings (38 %) between the OEM and Remanufacturing scenario occurred in the human toxicity category and was due to the reduction of virgin OEM cartridges, since a remanufactured cartridge displaces an OEM cartridge in the market. The most notable differences across the scenarios occurred in the agricultural land occupation, urban land occupation, and natural land transformation impact categories. The largest savings for the refill scenario compared to both remanufacturing and OEM scenarios occurred in the agricultural land occupation category because the largest contributor to this category came from the cartridges themselves, and from additional packaging and transportation associated with remanufacturing cartridges. Small savings were achieved in the urban land occupation and natural land transformation categories because the largest contributor for these categories came from the consumer transport activity, which remained

Table 6 Life cycle assessment of five OEM cartridges using ReCiPe (H) Midpoint method showing savings by impact category for remanufacturing and refilling scenarios under base assumptions

Impact category	Five OEM cartridges	Savings for five remanufactured cartridges (%)	Savings for one OEM+4 retail refills (%)
Climate change	9.8E+00 kg CO2 eq	10	20
Ozone depletion	1.3E-06 kg CFC-11 eq	9	9
Human toxicity	5.8E+00 kg 1,4-DB eq	38	63
Photochemical oxidant formation	3.7E-02 kg NMVOC	9	20
Particulate matter formation	1.1E-02 kg PM10 eq	11	24
Ionizing radiation	2.3E+00 kg U235 eq	14	26
Terrestrial acidification	3.1E-02 kg SO2 eq	11	24
Freshwater eutrophication	4.3E-03 kg P eq	36	60
Marine eutrophication	1.0E-02 kg N eq	14	32
Terrestrial ecotoxicity	1.3E-03 kg 1,4-DB eq	8	17
Freshwater ecotoxicity	9.3E-02 kg 1,4-DB eq	33	56
Marine ecotoxicity	9.4E-02 kg 1,4-DB eq	32	54
Agricultural land occupation	2.2E-01 m2a	9	68
Urban land occupation	3.0E-01 m2a	7	13
Natural land transformation	3.3E-03 m2	6	14
Water depletion	4.9E-02 m3	18	37
Metal depletion	1.1E+00 kg Fe eq	29	48
Fossil depletion	3.5E+00 kg oil eq	9	20

identical across the one at a time scenarios under base assumptions.

2.6 Sensitivity analysis

LCI and LCIA results were interpreted based on the goal and scope of the study to compare inkjet cartridge EOL routes and reuse options compared to OEM cartridges to achieve five use cycles using environmental indicators of interest. A sensitivity analysis was performed on key assumptions pertaining to consumer purchasing manner, consumer transport, recycled PET content in an OEM cartridge, and inkjet cartridge remanufacturing summarized in Table 5 and detailed as follows:

2.6.1 Consumer purchasing manner

Under one at a time purchasing, three cases were compared: five OEM cartridges, one OEM cartridge refilled four times, and five remanufactured cartridges. But five inkjet cartridge use cycles may be attained by varying the amount of inkjet cartridges (or alternatives) purchased at one time. Hence, there are several combinations of OEM and reuse cartridge alternatives that a consumer may select that still satisfy the functional unit of five inkjet cartridge use cycles while requiring less than five consumer transport activities. We specifically consider combinations of OEM cartridge and refill purchases.

2.6.2 Consumer transport

The base case assumes the consumer uses an automobile to make a dedicated visit to a retailer to purchase a single cartridge or refill a cartridge. Alternate modes of transportation, reducing the percent of the transport impact allocated to the cartridge (i.e., performing multiple tasks on the same trip), and reducing transport distance may enable consumers to reduce environmental impact associated with cartridge EOL decisions and reuse alternatives. Alternate consumer transport scenarios were investigated to demonstrate environmental savings that a consumer could achieve, such as walking or bicycling (0 % allocation), combining inkjet cartridge purchase or refill with weekly shopping (50 % allocation), and choosing to purchase a cartridge as part of an existing commute for a job (10 % allocation).

2.6.3 Recycled PET content of OEM inkjet cartridge

The base case assumed OEM inkjet cartridges were manufactured with 100 % virgin PET. But some OEM inkjet manufacturers incorporate recycled PET into inkjet cartridge production (Degher 2002). Five levels of recycled PET content in the representative inkjet cartridge were evaluated.

2.6.4 Inkjet cartridge remanufacturing

The base case assumed a remanufactured cartridge was produced by a highly efficient remanufacturer from a virgin inkjet cartridge that traveled 2,300 miles. The "best" remanufacturing case has the spent cartridge traveling 500 miles. The "worst" remanufacturing case pertains to a remanufactured cartridge produced by a lowly efficient remanufacturer from a mixed stream of spent cartridges that traveled 2,300 miles.

3 Results and discussion

The HP 60 inkjet cartridge bill of materials and processing data shown in Table 3 reflect the base case assumption of 100 % virgin material used in the production of an inkjet cartridge. Transportation from different manufacturing locations to their typical US port by barge and ground truck transportation to Rochester, NY is shown in Table 4.

Objective 1: determine hot spots in the life cycle From Table 3, the print head only represents 0.15 % (0.11 out of 75 g) of the packaged HP 60 inkjet cartridge, but is responsible for 20 % of the cartridge CED, as shown in Fig. 2. This finding is understandable, since the print head was modeled as an integrated circuit in ecoinvent. On the other hand, ink contributes 20 % (15 out of 75 g) by mass of a packaged OEM cartridge from Table 3, but only 3.2 % toward CED. These findings support our initial hypothesis that maximizing print head life through refilling or remanufacturing may enable users to reduce the environmental impact associated with inkjet cartridge consumption.

Objective 2: comparison of inkjet cartridge versions—OEM, refilled, and remanufactured Table 7 summarizes the GWP impact results on a per use cycle basis, excluding impacts from the consumer transport activity, so that a comparison of each cartridge alternative (i.e., OEM, remanufacture, and refill) can be compared with previous cartridge LCA studies summarized in Table 1. In order to report on a per use cycle basis, total impacts for each alternative (i.e., OEM, remanufacture, and refill) were summed and then divided by five. Since previous results varied in assumptions regarding the use phase, impact results for each alternative in Table 7 are presented using our base case, which excludes cartridge use phase impacts, as well as an alternate scenario that includes use as defined in section 2.4.5. The GWP impacts of the OEM cartridge (excluding use phase) from Table 7 compare similarly with the 1996 inkjet cartridge impact results found in Table 1 (Pollock and Coulon 1996). In our study, the contribution from the use phase is 0.38 kg CO2 eq per use cycle across all alternatives, which accounts for 36 to 57 % of total kg CO2 eq. This is not the case for the 2004 and 2008 studies,

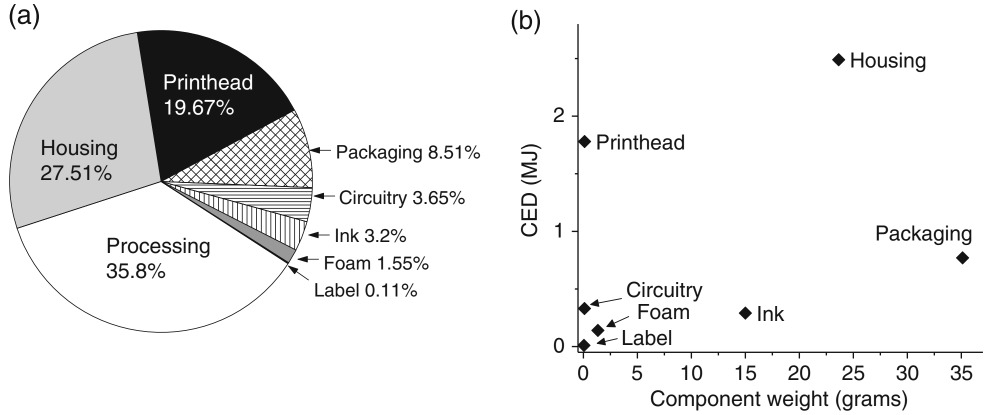

Fig. 2 Cumulative energy demand (MJ) (**a**) contribution by component and production processing (**b**) compared to component weight

which range from 60 to 96 % of total kg CO2 eq (First Environment Inc., October 2004; Four Elements Consulting LLC 2008) due to the inclusion of a "usability" metric for printed output. The refill case offered the lowest environmental impact, with a 76 % reduction in GWP impact when use phase is excluded and a 37 % reduction in GWP impact even when considering cartridge use and the associated power use and paper consumption impacts. Next, the baseline remanufacturing case provided an 18 % savings in GWP impact including use phase and a 36 % savings in GWP impact excluding use phase compared to the OEM alternative.

These findings indicate that refilling used cartridges or purchasing remanufactured cartridges both offer environmental improvement compared to purchasing new OEM cartridges, when assessed on the basis of one use cycle. To put the potential environmental savings into context, the natural question that comes to mind is: How many black inkjet cartridges will a typical consumer require for an inkjet printer? A 2007 report (Stobbe 2007) focused on "imaging equipment" in Europe, estimated that a personal inkjet printer would be used by a consumer for a period of four years with an annual output of 1,040 A4 size pages with the printing on each page composed of 70 % black ink and 30 % color ink. If we assume a HP 60 black inkjet cartridge yields approximately 100 A4 pages, then over four years the typical consumer would require 28 black inkjet cartridge use cycles. When evaluating options on the basis of the functional unit of five inkjet cartridge use cycles, the analysis must also comprehend consumer transport activities between use cycles—particularly travel to a retailer to either refill an existing cartridge or purchase a new one. The manner and mode by which consumers purchase cartridges have not been addressed by the previous cartridge LCA studies summarized in Table 1. Since an 8-km trip by automobile, fully allocated to the purchase of one inkjet cartridge accounts for 1.44 kg CO2 eq for GWP (25 MJ for CED), variability in the consumer transport activity can substantially influence results. Figure 3 illustrates how results are influenced by select assumptions that affect mode of travel, allocation percent, and manner (i.e., number of trips) for the consumer transport activity can have on the results. Results in Fig. 3 are divided between one OEM cartridge that is refilled four consecutive times (and the degree to which trips to a retailer are allocated to the cartridge) and five OEM cartridges (either purchased consecutively in five trips or all at once in one trip), the latter assuming that 100 % of the transport activity is allocable to the cartridge. For our base assumptions, refilling is the best cartridge option for one at a time purchasers making dedicated trips by automobile at 138 MJ. This refilling option can be reduced to as low as 13 MJ when one at a time purchasers chose an impact-free (0 % allocated) transportation method, like walking or bicycling to the retailer. In the case of five OEM cartridges, the minimum total impact possible is 50 MJ, which includes the OEM processes and no (or 0 %) consumer transportation impact. Including the consumer transportation in the five OEM cartridge case scenarios results in impact from 175 MJ

Table 7 Global warming potential impact results (kg CO2 eq) per cartridge use cycle with contribution by stage, excluding consumer transport impacts

Cartridge	OEM		OEM		Remanufacture		Remanufacture		Refill		Refill	
Paper	None		100 pp		None		100 pp		None		100 pp	
Production	0.43	82 %	0.43	40 %	0.26	78 %	0.26	30 %	0.11	86 %	0.11	16 %
Distribution	0.06	11 %	0.06	5 %	0.05	14 %	0.05	5 %	0.01	9 %	0.01	2 %
Use	0	0 %	0.38	36 %	0	0 %	0.38	43 %	0	0 %	0.38	57 %
EOL	0.04	7 %	0.20	19 %	0.03	8 %	0.19	22 %	0.01	6 %	0.17	26 %
Total	0.52	100 %	1.07	100 %	0.33	100 %	0.88	100 %	0.13	100 %	0.67	100 %

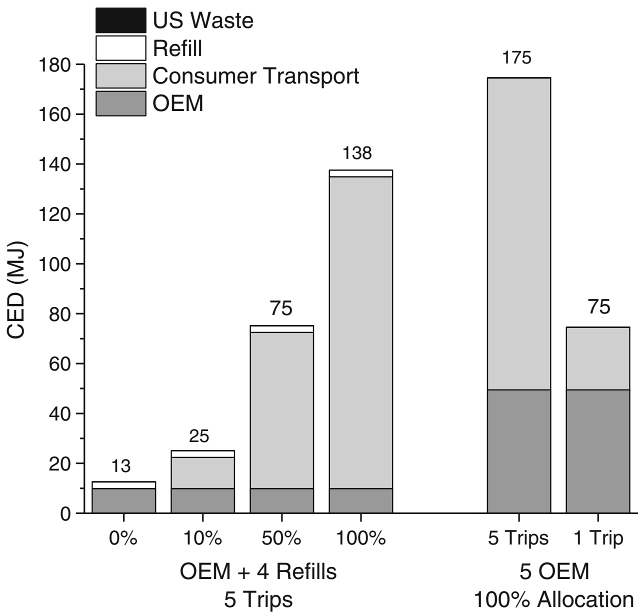

Fig. 3 Cumulative Energy Demand (CED) per five cartridge use cycles. Left: one OEM cartridge refilled consecutively four times, with increasing percentages of transportation impact allocated to the cartridge life cycle; Right: five OEM cartridges purchased consecutively in five trips or all at once in a single trip. Results are highly sensitive to consumer transport assumptions

for the base assumption of five trips and 75 MJ for a single trip. Notably, a consumer that buys five OEM cartridges all at once is equivalent to a consumer selecting refilling one at a time with transport allocated at 50 %.

If consumers purchase inkjet cartridges one at a time, then these results show refilling provides the lowest environmental impact, regardless of other consumer transport factors. However, removal of the one at a time purchasing constraint enables a consumer to achieve additional environmental improvement by reducing the number of trips required to obtain the functional unit of five cartridge use cycles. Since the impact for a refill is approximately 11 % of the CED value for a fully allocated trip to a retailer by automobile, the environmental savings from reducing the number of consumer transport activities overwhelms savings provided from refilling. If the allocation percentage associated with getting a refill for an 8 km trip is less than 11 % (i.e., 89 % of the trip impact can be allocated to other activities like grocery shopping, leisure activities, or work commutes), then refilling will provide more environmental savings than eliminating one trip. This demonstrates that results are extremely sensitive to consumer transport decisions.

So far, we have looked at either purchasing all OEM cartridges or refilling one OEM cartridge four subsequent times. But five inkjet cartridge use cycles may be obtained in other combinations, like purchasing multiple OEM cartridges at a time with subsequent refills in another retailer visit. Figure 4 considers the CED for combinations of OEM cartridges and refills that achieve five use cycles with consumer transports fully allocated to the cartridge life cycles. Here, we see that reducing the environmental impacts of the consumer transport activity outperforms the environmental savings that can be achieved by refilling. Additional consumer trips may be incurred if a consumer pursuing refilling discovers a “failed refill” after leaving the retail store. In this case, the consumer will have to make another roundtrip to the retailer in order to purchase either a new or remanufactured cartridge to replace the defective refilled cartridge. Cartridge substitution would roughly add 51 to 80 % impact for GWP (from Table 7), but the impact for the additional consumer transport activity depends upon mode and allocation.

Objective 3: EOL routes Consumers also have a variety of ways to discard an inkjet cartridge. Remanufacture and refill routes considered in this study may result in an inkjet cartridge seeing one or more additional use cycles. However, market data indicate that typical EOL routes of landfill, incineration, recycle, and municipal solid waste are more utilized than those that lead to inkjet cartridge reuse. Figures 5 and 6 illustrate the CED and GWP contribution of each EOL route compared to impacts for a single OEM cartridge delivered to a retailer in Rochester, NY, USA.

3.1 Landfill, incineration, and municipal solid waste

The contribution of these EOL routes to total CED are relatively small, compared to the manufacture of new cartridges, with increasing impact observed in (1) incineration (0.18 %), (2) US Waste (0.20 %) and (3) landfill (0.35 %), respectively, although the maximum difference between any of these EOL routes is only 0.2 %. On the other hand, the contribution of these EOL routes for the GWP100 impact assessment method

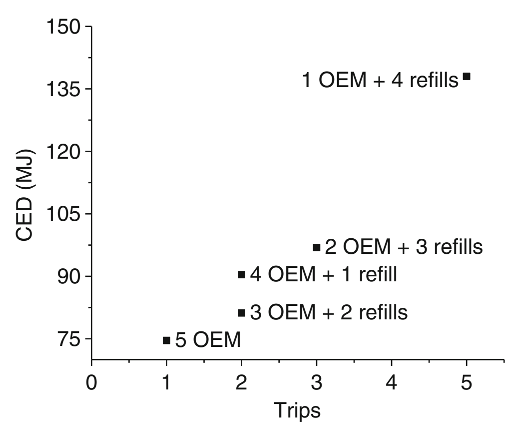

Fig. 4 Comparison of OEM and refill combination scenarios for fully allocated consumer transport activities. Reducing intensity of consumer transport offers more environmental savings than choosing a refill over an OEM cartridge to achieve five use cycles

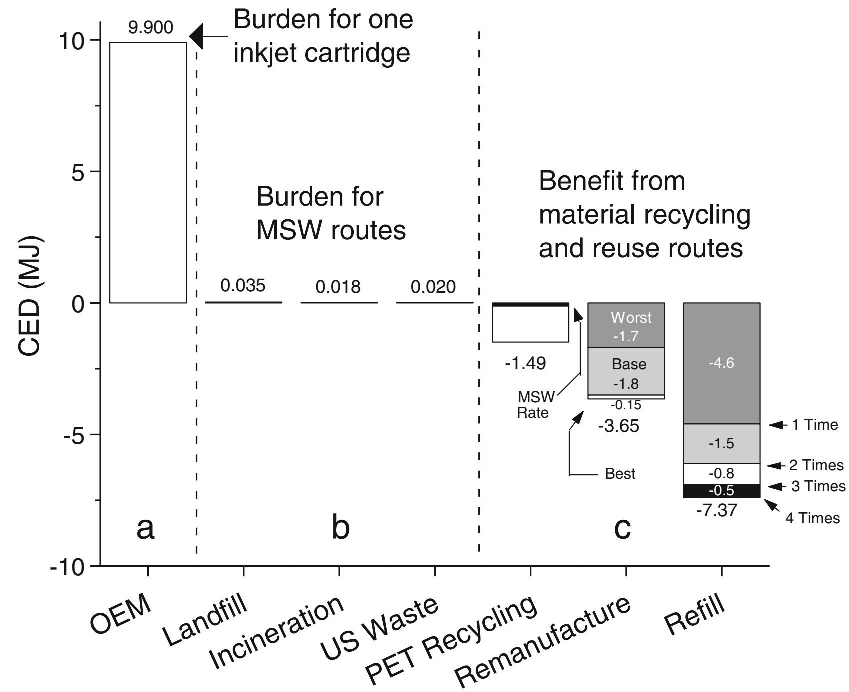

Fig. 5 CED contribution for each EOL route relative to the **a** total CED value for producing one OEM cartridge available for purchase in Rochester, NY, **b** shows the additional burden for municipal solid waste routes, and **c** shows the variable benefit attainable from recycling PET at average (8 %, comparable to MSW recycling) and best rates (100 % closed loop), remanufacturing the entire cartridge under Worst-, Base-, and Best-case scenarios, and refilling the cartridge up to four times not including consumer transport

range from 8 to 12 % with US Waste now having the lowest impact and landfill the greatest, due to the potential for methane emissions.

3.2 Recycling

Recycled PET from spent inkjet cartridges and water bottles is used in the production of OEM inkjet cartridges (Degher 2002) and provides a credit of approximately 1.49 MJ, which is 15 % of the CED for the OEM cartridge. This credit from closed loop recycling is much higher than the 0.12 MJ credit that would be achieved if PET was recycled at 8.2 % from the US municipal waste stream (Environmental Protection Agency 2012). Similarly, recycling an inkjet cartridge provides a credit of up to 0.05 kg CO2 eq (10 %) for the GWP impact assessment method. Table 8 expands on the GWP and CED impact performance for cartridges with 0, 30, 50, 70, and 100 % recycled PET content. More than 70 % of a HP 60

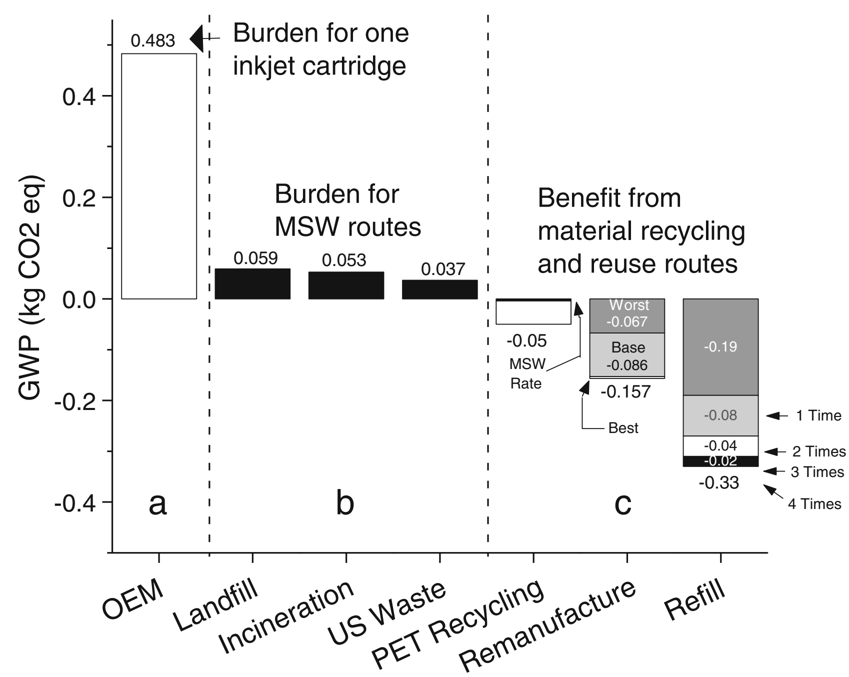

Fig. 6 GWP contribution for each EOL route relative to the **a** total GWP value for one OEM cartridge available for purchase in Rochester, NY, **b** shows the additional burden for municipal solid waste routes, and **c** shows the variable benefit attainable from recycling PET at average (8 %, comparable to MSW recycling) and best rates (100 % closed loop), remanufacturing the entire cartridge under Worst-, Base-, and Best-case scenarios, and refilling the cartridge up to four times not including consumer transport

Table 8 GWP and CED impact savings by recycled PET content in OEM cartridge, excluding use and customer transport impacts

Impact per use cycle	GWP 100a (kg CO2 eq)	GWP savings (%)	CED (MJ)	CED savings (%)
Virgin PET OEM Inkjet	0.48	N/A	9.90	N/A
30 % recycled PET OEM Inkjet	0.47	3.5	9.40	5.4
50 % recycled PET OEM Inkjet	0.46	5.4	9.12	7.9
70 % recycled PET OEM Inkjet	0.45	7.2	8.83	10.8
100 % recycled PET OEM Inkjet	0.43	10.1	8.41	15.0

cartridge body (by weight) is currently recycled content from used HP cartridges and other sources such as water bottles (Hewlett-Packard Development Company L.P. 2008). At 70 % recycled PET content, there is only modest environmental improvement for both GWP and CED.

3.3 Remanufacture

The maximum theoretical reduction in environmental impact from reuse may be represented by $[1-(1/(1+n))]\times 100$ %, where "n" reflects the number of reuse cycles (Goldey et al. 2010). For one inkjet cartridge remanufacturing cycle, the maximum theoretical reduction in CED would be 4.95 MJ (50 %×9.9 MJ), provided there were no additional actions done to the inkjet cartridge to enable another reuse cycle. But a remanufactured cartridge can vary in environmental impact due to numerous factors. Three sources of variability in remanufactured cartridge environmental impact investigated in this study were spent cartridge travel distance (500 and 2,300 miles), spent cartridge quality (virgin and mixed input), and remanufacturer efficiency (high, moderate, and low). Figure 7 illustrates the effect on GWP from each of these sources of variability. From Fig. 7, it is obvious that remanufacturing efficiency has the greatest effect on GWP impact for a remanufactured cartridge, followed with spent cartridge input type having a slightly greater effect than cartridge travel distance. Although it is impossible to characterize the remanufacturing cartridge market due to its dynamic nature, consolidation in the inkjet cartridge remanufacturing sector serving the US is more likely to result in large remanufacturers that leverage their market power to claim high-quality cartridges as input to their highly efficient operations. A large remanufacturer of this type would produce an inkjet cartridge with a value of 0.33 kg CO2 eq, labeled as "Base" on Fig. 7 The base case is only marginally higher than the "Best" case of a highly efficient remanufacturer processing the virgin cartridges that traveled 500 miles at a value of 0.3265 kg CO2 eq. This result suggests that environmental improvement obtained from increased efficiency through consolidation may lead to aggregate environmental improvement in the sector, since environmental gains from improved efficiency outperform environmental impacts from increased cartridge travel distance.

Notably, the worst case remanufacturing case provides a 14 % improvement compared to the benefit from recycling PET from a spent cartridge. However, from a GWP impact

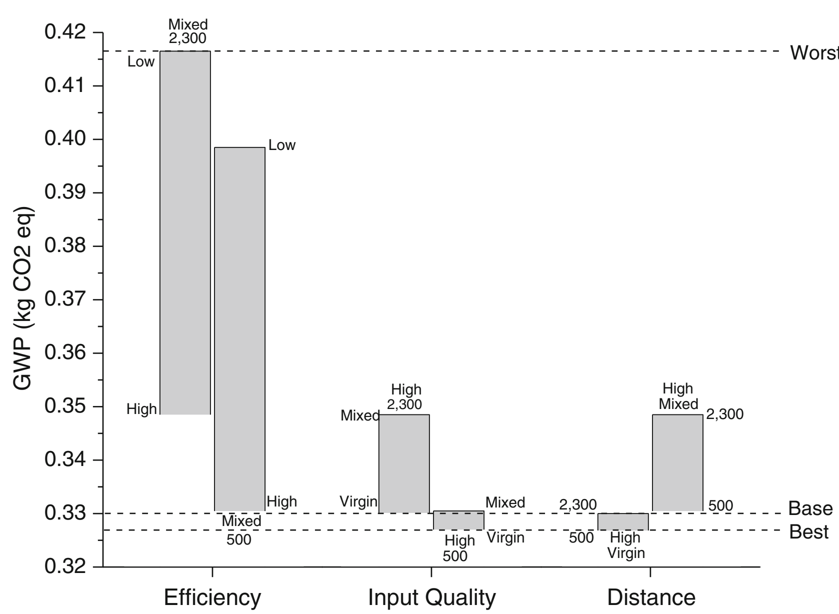

Fig. 7 GWP impact for remanufacturing inkjet cartridges disaggregated by remanufacturer efficiency (*low* and *high*), input cartridge quality (*virgin* and *mixed*) and spent cartridge travel distance (500 and 2,300 miles). Remanufacturing efficiency considers the number of input cartridges required to produce one remanufactured cartridge (1.09 representing high efficiency and 3.57 representing low efficiency)

assessment perspective, the worst case remanufactured cartridge case provides a 33 % improvement over recycling. Where economically motivated consolidation in the cartridge remanufacturing sector may lead to environmental benefits, profit motivated collection firms of spent cartridges may route less desirable cartridges to remanufacturers instead of incurring a cost associated with recycling them at the onset. Spent cartridges of this type may accrue environmental impact from transportation and a failed remanufacturing attempt.

3.4 Refill

From Figs. 5 and 6, a single refill cycle offers a greater reduction in environmental impact than any of the remanufacturing scenarios. The first reuse cycle from refilling provides a reduction in CED of 4.6 MJ, just 7 % less than the theoretical maximum reduction of 4.95 MJ. As expected, subsequent refills provide further environmental benefit, with four refills providing a reduction of 7.37 MJ. Even though refilling provides the best opportunity to reduce environmental impact by extending the usable life of an inkjet cartridge, the sensitivity of these findings to the consumer transport activity suggest that maximizing environmental savings from reducing consumer transport impacts should be examined first. Recall that a fully allocated consumer transport activity to purchase an inkjet cartridge alternative is approximately 2.5 times the CED (3 times the GWP) impact of an OEM cartridge.

4 Conclusions and recommendations

Consistent with conventional wisdom, we find reuse of an inkjet cartridge can provide an environmental benefit over a new OEM inkjet cartridge. In exploring inkjet cartridge reuse, we investigated two options readily available to US consumers, (1) purchasing a remanufactured inkjet cartridge, and (2) inkjet cartridge refilling at a local retailer. The latter alternative enables a consumer to reuse an inkjet cartridge multiple times, whereas a spent inkjet cartridge typically undergoes one remanufacturing cycle. With a functional unit of five inkjet cartridge use cycles, results were highly sensitive to how a consumer went about purchasing an inkjet cartridge use cycle and the associated transportation activity and impact. Based on these findings, broader implications are discussed below.

4.1 Sequential purchasers

For those consumers that purchase and use one inkjet cartridge at a time, and then repeat the cycle, refilling an OEM cartridge four consecutive times provides the best alternative for reducing environmental impact associated with inkjet cartridge consumption. Although inkjet cartridge refilling cycles offer the greatest opportunity for environmental improvement, refilling may not appeal to all consumers. For those consumers that don't want to retain and refill cartridges, substituting remanufactured cartridges for OEM cartridges will provide environmental improvement, but at more modest levels. Further improvement in environmental performance may be obtained through choosing a mode of travel with lower impacts.

4.2 Multiple cartridge purchasers

Consumers that already minimize the environmental impact associated with consumer transport by purchasing multiple cartridges in a single trip to a retailer should not pursue refilling if doing so leads to a net increase in environmental impact from additional travel. However, substituting cartridge refills in place of OEM cartridges will yield environmental savings when holding consumer transport constant. A consumer that purchases two cartridges at a time could achieve an environmental benefit by taking two empty OEM cartridges to a retailer and getting both refilled as opposed to purchasing two more OEM or remanufactured cartridges.

The recommendation of what should be done with a spent inkjet cartridge is less obvious, since traditional EOL routes vary for GWP and CED impact categories. However, our findings suggest the following guidelines:

4.3 OEM cartridge

A spent OEM cartridge is a preferred input (i.e., "virgin" cartridge) for both inkjet cartridge remanufacturers and consumers that want to pursue cartridge refilling. Consistent with our findings, a cartridge of this type should be directed to an EOL route that leads to reuse.

4.4 Remanufactured cartridge

Since inkjet cartridge remanufacturers have a strong preference for virgin OEM cartridges, previously remanufactured cartridges should be directed to cartridge recycling as the first best option. Even though the results indicate additional environmental savings may be achieved by the worst case remanufacturer that have some non-virgin cartridges in their input stream, environmental impact incurred from less desirable cartridges being sent to remanufacturers is likely to result in more cumulative environmental harm than if the cartridge was directed to an efficient recycling path.

4.5 Refilled cartridge

A spent cartridge that has been successfully refilled four times, or has failed prematurely, should be directed to cartridge

recycling as in the recommendation for a previously remanufactured cartridge above.

Since all recycling routes do not have the same environmental impact, care should be taken by consumers in selecting a recycling route. Although OEMs accept their own cartridges for recycling, previously remanufactured or refilled cartridges are excluded from voluntary recycling by OEMs. Consumers desiring to recycle spent remanufactured cartridges often drop them off at a retailer for recycling, which requires transport. Since recycling of PET from cartridges provides a 10 % GWP reduction in impact (15 % CED reduction) in the most optimistic case, the environmental harm from the consumer transport activity may erode or exceed environmental savings of inkjet cartridge recycling.

Since consumer decisions related to the manner of purchase/disposal and mode of travel have a significant effect on environmental impact for achieving five use cycles, it is worthwhile to investigate observations from the US market that may influence consumer travel. HP estimates that if all inkjet cartridges returned using return envelopes in 2008 were instead returned via consumers taking empty cartridges to retailer Staples for consolidated shipping to HP's recycling center, 600,000 lbs of shipping materials would be eliminated (Roulston and Heinrich 2008). While reduced packaging and consolidated shipping offers environmental benefits over cartridges returned using return envelopes, the method consumers choose to route their empty cartridges to stores may cut into these environmental benefits, or even make the in-store return option result in worse environmental performance. As seen from analysis performed here, consumer travel to (and from) a retailer represents the largest portion of environmental impact for an inkjet cartridge use cycle. Assuming the number of returned cartridges remains the same, if HP's decision to eliminate return envelopes with new cartridge packaging results in more consumer trips to a retailer, then it is likely that environmental performance of the Staples return system may be worse than the return envelope system.

Staples policy for cartridge recycling may further promote additional consumer trips to Staples stores even for consumers that utilize Staples mail order services. For instance, Staples return policy provides a store credit of $2 (limit of ten cartridges per month) for each cartridge brought to a Staples store for recycling, but no financial credit for cartridges returned for recycling through parcel delivery (Staples 2012).

Market changes may also encourage more consumer travel related to inkjet cartridge use. As stated earlier, OEMs have expanded cartridge offerings to include low- and high-yield alternatives. If a consumer purchased low-yield cartridges (e.g., HP 60) which provides one-third the rated output of a high-yield cartridge (e.g., HP 60XL), consumer transport could increase threefold over the high-yield alternative. Aside from an increased likelihood of consumer transport, printing systems with low-yield inkjet cartridges have worse carbon footprint performance on a per image printed basis than printing systems using high-yield inkjet cartridges (Ord et al. 2010). Locating a more durable print head within the inkjet printer and switching the inkjet cartridges to ink tanks would reduce "resource consumption during product manufacturing by 40 %, air emissions by 67 %, solid waste generation by 95 %, and wastewater by 92 % per page printed" (Laszewski and Carey 2002).

Given the complexity of understanding and modeling consumer purchase and disposal decision making for inkjet cartridge alternatives, future research is required to investigate the trade-offs in convenience, cost and environmental impact associated with each purchase and disposal option. Understanding how consumers perceive these trade-offs may illuminate opportunities to design and implement incentives to shift consumers toward purchase and disposal options with lower environmental impacts. While focused specifically on cartridge systems here, these outcomes are applicable to other examples of consumer decisions across the "green" product space.

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